PREVENTING COAL-MINE FIRES CAUSED BY ELECTRICAL EQUIPMENT

BY C. L. BROWN

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INTRODUCTION

The frequency of mine fires during recent years, with an apparent increase in recent months, has focused attention on the necessity of reducing this hazard by every means possible. Investigation reports are available on 51 mine fires of electrical origin between August 15, 1949, and August 16, 1954. Nine other fires in the same period were suspected as being of electrical origin. Every mine fire is a potential hazard to underground workmen; it is remarkable that only six lives were lost as a result of these fires, since the injury list was very high.

Modern mining methods, with increased power demands and extended distribution systems underground, involve greater electrical hazards and possibilities of costly production delays as a result of inadequate electrical service. Improvements in electric-power-distribution facilities in many underground coal mines is desirable. The purpose of this paper is to show the need for this improvement as revealed by studies and investigations of electric-power-distribution systems representative of those in a large number of coal mines.

ACKNOWLEDGMENT

The assistance and cooperation of the officials at coal mines where electrical surveys have been made and the assistance of engineers and coal-mine inspectors of the Bureau are gratefully acknowledged.

DESCRIPTION OF COAL-MINE POWER-DISTRIBUTION SYSTEMS AND EQUIPMENT

Electric-Power Source and Application

Electric power is utilized in the form of alternating current for operating all equipment in a few coal mines in the United States; however, the most common system is to supply direct current to operate haulage and face equipment, supplemented in most instances with alternating current to operate such permanent equipment as hoists, pumps, etc. If haulage is by trolley locomotives, the track is used as a power conductor, but in trackless mining, direct-current electric power requires two similar conductors for transmission, and the distribution system can be ungrounded.

Common transmission voltages for alternating current in coal mines are 2,200 and 4,160; however, other voltages up to 13,000 have been used in a few instances. The transmission voltage is usually transformed to a lower value, except for power supplied to large equipment. Standard alternating-current voltages for face equipment are 220 and 440. The voltage selected is usually governed by preference or local regulations. Modern transformers are nonflammable-oil-filled, air-cooled or inert-gas-filled. Transformers for use near working areas are usually portable, since most mining methods require that they be moved frequently. Alternating current has certain inherent characteristics that make its use preferred by many engineers. For example, because motorized equipment operated on

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alternating current will not perform as satisfactorily on low voltage as will equipment operated on direct current, secondary alternating-current transmission lines must be short, thereby keeping power loss at a minimum and making possible dependable short-circuit protection. These are two important factors that cannot be attained on any circuit that is extended too far from the power source.

Several reasons may be given for the popularity of direct current in coal mines before the period of general mechanization. In the early period, electric power was not available through public utilities, which necessitated installing private generating plants at mines. Direct-current generators were considered best suited for this application because of the overall simplicity of the system. Likewise, the characteristics of direct-current motors and controls make them superior to alternating-current equipment for mine-haulage locomotives. It is worthy of note that all mining equipment requiring electric motors, except locomotives, can be designed to operate on alternating current with performance equal to that of direct-current equipment.

Today a large percentage of all electric power used in the coal-mining industry is purchased; however, many small mines still maintain their own plants. Only a few private generating plants remain in use at large mines. Most of the electric power purchased is in the form of alternating current, which necessitates the use of conversion equipment at mines where direct current is required. Only in recent years has conversion equipment been made portable. Formerly, the cost of relocating substations to keep pace with development was a factor that often resulted in inadequate power service in face areas. This problem has been relieved somewhat by the introduction of portable substations into mines and the development of conversion equipment readily adaptable to this service. Motor-generator sets and synchronous converters, with motor-generator sets leading slightly in popularity, were used almost exclusively for power conversion up to about 18 years ago. Most new conversion equipment sold to the coal-mining industry since that time has been mercury-arc rectifiers. Recently, there has been considerable activity in the development of selenium rectifiers, and several units have been installed for power conversion at coal mines.

Methods of Power Distribution

The simplicity of alternating-current power distribution in coal mines where modern transformers are maintained properly near load centers has made possible a very good record as regards fires in secondary alternating-current power circuits. An analysis of this situation indicates that one of the primary reasons for this success may be the ease with which short-circuit protection can be provided on the average circuit of this type. This protection is possible because the circuits are generally not overextended and the loads are reasonably well balanced on each phase. The secondary-power supply from one transformer station is not interconnected with that of another station in common practice. Although transformer stations have been interconnected in a few instances, the practice is discouraged, except in an emergency, because of fire and shock hazards that are introduced.

Throughout the years, direct-current power circuits have been interconnected in coal mines to permit parallel operation of substations. This has been done to take advantage of the diversity of widely separated loads, thereby reducing the total substation capacity required, and also for more economical power transmission. Today a large number of mines have 12 or more substations operating in parallel on as much as 50 miles of circuit. The hazards of this method of operation have been demonstrated but they frequently are not recognized. Fortunately many coal companies have taken measures to minimize them. Following a major disaster a few years ago

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in which a large number of lives were lost as a result of a fire from a trolley-wire system, it was evident that improvement in the safety of underground power distribution must be made. Representatives of the coal-mining industry, Bureau of Mines, States, and manufacturers banded together in an effort to find a solution to the inherent hazards of direct-current power distribution in coal mines. After careful study of the various phases of underground power applications, standards were set that were considered essential for safe and efficient operation. Standards for protection of direct-current power circuits prepared by one of the committees in this work have been adopted in Bureau of Mines Bulletin 514.2/ Several leading coal companies have recognized the hazards involved in their particular systems and have taken the necessary steps to minimize them.

Although several solutions, or combinations thereof, are possible to correct deficiencies in the safety of power-distribution systems, two basic methods have been followed to accomplish the desired results. It has been found possible to isolate substations in some mines, thereby reducing the hazards from short circuits; in other mines, parallel operation of substations is considered necessary, and, in order to operate safely, suitable protective devices have been installed in lieu of permanently isolating a large number of substations. The object in either case is to prevent power from a remote source feeding into a short circuit, a condition which has caused many mine fires in the past. Difficulty always arises where a mine power-distribution system has inadequate current-carrying capacity. The result is excessive power loss, poor equipment performance, and difficulty in providing satisfactory short-circuit protection for equipment and circuits. The latter deficiency is always cause for concern in preventing fires from power circuits.

Short-Circuit Protection of Power Circuits

Unfortunately, proper consideration frequently is not given to the power-distribution-system design and to application of the protective devices available for guarding against the hazards of short circuits. The problems of power distribution underground require as much or more engineering as installations on the surface. An installation may be well designed originally; but, through additions and extensions without regard for basic principles, it may become hazardous and inefficient. Perhaps one of the electrical devices most commonly misused is the substation circuit breaker. This device was designed primarily to protect the substation equipment. Station circuit breakers feeding large systems offer only a limited amount of protection against short circuit for the individual power circuits leaving the substation. For a given overcurrent setting, a protective device has a definite operating range or limit from its point of location. This range is determined by the voltage impressed on the circuit, the value of the setting, and the total resistance of the circuit. Thus, the higher the setting for a given circuit resistance and voltage, the shorter will be the effective range. Likewise, the higher the circuit resistance is for a given voltage and overcurrent setting, the shorter will be the range. It is the disregard for these principles that has resulted in hazardous conditions in connection with power distribution in coal mines.

The limitations of substation breakers when depended upon for short-circuit protection of the distribution system can be illustrated by a simple problem in which a substation is supplying an isolated circuit, with the following information known:

2/ Bureau of Mines, American Standard Safety Code for Installing and Using Electrical Equipment In and About Coal Mines (M2.1), Bull. 514, 1952, 28 pp.

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300-kilowatt substation
Output at substation - 275 volts
Overcurrent setting at substation circuit breaker - 1,600 amperes
Size of track rails - 40 pounds per yard
Size of trolley wire - 4/0
Resistance per mile of 40-pound track - 0.07047 ohm
Resistance per mile of 4/0 trolley wire - 0.26400 ohm
Total circuit resistance per mile - 0.33447 ohm

The theoretical effective range of the circuit breaker may be determined by Ohm's law, using the known factors. The applied voltage (275) and the overcurrent setting (1,600) being given, the unknown to be solved is the resistance through which the voltage will cause this value of current to flow.

By Ohm's law, resistance = $\frac{\text{voltage}}{\text{current}}$,

then by substitution:

$$\text{Resistance} = \frac{275}{1,600} \text{ or } 0.17187 \text{ ohm.}$$

Therefore, the maximum theoretical range of the circuit breaker is $\frac{0.17187}{0.33447}$ or 0.51 mile.

The range of approximately 1/2 mile as determined in the above manner is based on the following assumptions:

(1) All load on the station concentrated at one point, (2) maximum conductivity of the power circuit, (3) zero resistance through the load, and (4) constant voltage applied. An analysis of the assumed factors will reveal that in actual practice some of the factors may affect the circuit-breaker range adversely. For example, direct-current circuits in coal mines rarely meet the theoretical value for resistance, and , although the voltage output of some substations may vary only slightly with change in load, the voltage characteristics of many are such that the voltage at full load is less than at no load. Therefore, the effective range of the circuit breakers may be less than the theoretical range under actual operating conditions in coal mines. This is a matter that must be taken into account when overcurrent settings are made. The effective range of circuit breakers may be 25 percent less than the theoretical range where maintenance is poor. Any extension of a power circuit beyond the effective range of the overcurrent device creates a hazard under conditions of a short circuit.

The effect of the applied voltage on the current-carrying capacity of a circuit is often lost sight of in coal-mine operations. The importance of good voltage regulation on a direct-current circuit, with regard to current-carrying capacity, is indicated by a study of the values in figure 1. For example, a circuit with a total resistance of 0.05 ohm and an impressed voltage of 300 will deliver 6,000 amperes on short circuit at the inby end, whereas the same circuit will have a short-circuit capacity of only 4,000 amperes when the impressed voltage is 200. This relation is an important factor in selecting protective devices and the overcurrent settings thereon for branch as well as main power circuits. Reports have been received indicating that short circuits in trailing cables do not always actuate the fuse in the power tap. In some cases the fuses were found to bee too large for the particular application. In other cases investigations revealed that poor voltage regulation in the area was an important contributing factor. The deficiency resulted from

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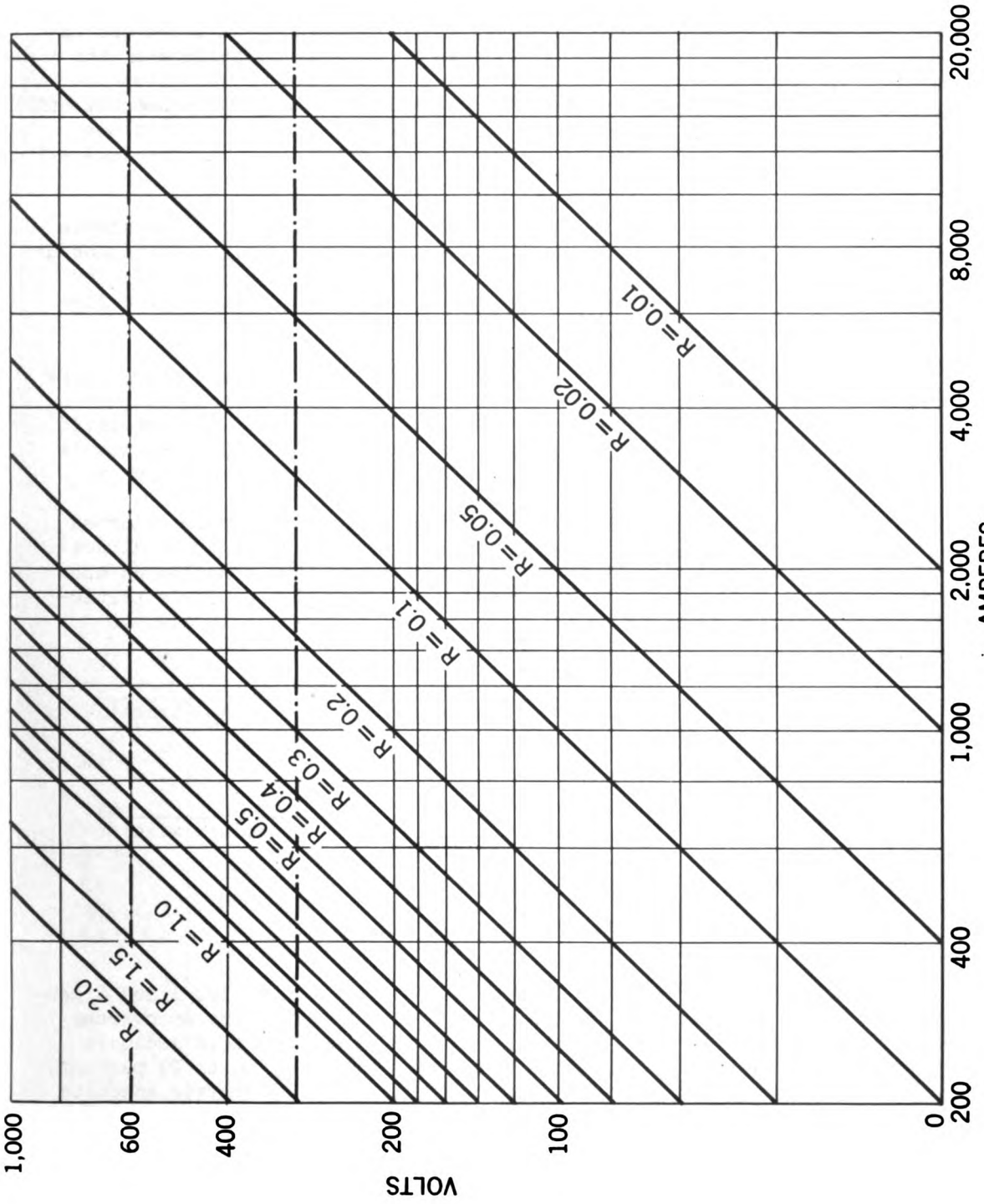

Figure 1. - Application of Ohm's law, $\frac{E}{I} = R$.

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excessive resistance in the power circuits caused by improper maintenance and extensions of circuits beyond the economical point of power transmission. It is not uncommon to place the blame for fires that result from this cause on failure of the protective device to perform properly, however, the device could not function because of existing conditions. Overcurrent devices employed to protect equipment and circuits depend upon the flow of current to actuate them. If the circuit is not capable of carrying current equivalent to the overcurrent setting, then the device cannot function.

Two other reasons for poor protection of feeder circuits are: (1) The simple formulas for determining safety are not well understood by many mine electricians or under pressure of daily duties they do not have time to develop them; and (2) few men recognize the need for periodic testing of all breakers to determine if a fire could be started.

Tests of a circuit breaker are very simple and are always the best check. One method of making a performance test is to open the breaker and then establish a short circuit from the trolley wire or feeder. If the breaker is of the automatic reclosing type, it should be impossible for it to close when the control switch is closed; if of the manual type, it should be impossible for it to be kept closed.

Typical distribution plans of many large, representative mines were selected as examples for preparing data on resistance and short-circuit capacity of direct-current power circuits, as given in tables 1 and 2. Although the examples do not cover all cases, they probably apply to the majority. Interpolation for a particular circuit not covered will not be difficult. Maximum short-circuit current values were determined from the formula:

$$\text{Amperes (short circuit)} = \frac{\text{E (system volts)}}{R_1\ \text{(feeder cable and trolley wire)} + R_2\ \text{(track)}}.$$

Copper resistance was determined by:

$$R_1\ \text{(ohms)} = \frac{\text{Distance (feet)} \times 10.58}{\text{Circular mils (area of feeder cable + area of trolley wire)}}.$$

Track resistances were determined from:

$$R_2\ \text{(ohms)} = \frac{\text{Distance (feet)}}{\text{Pounds (per yd. of rail)} \times 1873\ \text{(constant)}}.$$

Overcurrent-setting values in the 2 columns on the right in tables 1 and 2 generally should be reduced by 5 percent to insure safe ampere selections on overcurrent relays with close calibrations. If track bonds are known to be in mediocre condition, it would be worthwhile to further reduce the values by 10 to 20 percent, but this step may be disregarded by mines using welded rail or a separate adequate negative cable for the return circuit. For intermediate distances not shown in the tables, it would be good practice to select the next greatest distance. Every 6 months, or oftener if required, new settings should be selected for distances known to have increased since the last settings. Circuit-breaker settings for 550-volt service may be obtained, of course, by doubling the values listed for 275 volts.

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TABLE 1. - Resistance and short circuit capacity, direct-current power circuits (multiple-feeder applications, not sectionalized)1/

Distance between substations, miles	Feeder cable size, cir. mils	Trolley-wire size	Rail weight, lb. per yard	Total copper resistance, ohm	Total track resistance, ohm	Total circuit resistance, ohm	Max. instantaneous current-amperes	
							At 275 v.	At 290 v.
	1,500,000		90	0.058803	0.062645	0.121448	2,264	2,388
2		9	70		.080543	.139346	1,974	2,081
(10,560 ft.)		Section	90		.062645	.142448	1,931	2,036
	1,000,000		70	.079803	.080543	.160346	1,715	1,809
	1,500,000		90	.055127	.058729	.113856	2,415	2,547
1-7/8		9	70		.075509	.130636	2,105	2,220
(9,900 ft.)		Section	90		.058729	.133545	2,059	2,172
	1,000,000		70	.074816	.075509	.150325	1,829	1,929
	1,500,000		90	.051452	.054814	.106266	2,588	2,729
1-3/4		9	70		.070475	.121927	2,255	2,378
(9,240 ft.)		Section	90		.054814	.124642	2,206	2,327
	1,000,000		70	.069828	.070475	.140303	1,960	2,067
	1,500,000		90	.047777	.050899	.098676	2,787	2,939
1-5/8		9	70		.065441	.113218	2,429	2,561
(8,580 ft.)		Section	90		.050899	.115739	2,376	2,506
	1,000,000		70	.064840	.065441	.130281	2,111	2,226
	1,500,000		90	.044102	.046983	.091085	3,019	3,184
1-1/2		9	70		.060407	.104509	2,631	2,775
(7,920 ft.)		Section	90		.046983	.106836	2,574	2,714
	1,000,000		70	.059853	.060407	.120260	2,287	2,411
	1,500,000		90	.04027	.043068	.083495	3,294	3,473
1-3/8		9	70		.055373	.095800	2,871	3,027
(7,260 ft.)		Section	90		.043068	.097933	2,808	2,961
	1,000,000		70	.054865	.055373	.110238	2,495	2,631
	1,500,000		90	.036752	.039153	.075905	3,623	3,821
1-1/4		9	70		.050339	.087091	3,157	3,330
(6,600 ft.)		Section	90		.039153	.089030	3,089	3,257
	1,000,000		70	.049877	.050339	.100216	2,744	2,894
	1,000,000		90	.044889	.035238	.080127	3,432	3,619
1-1/8		9	70		.045305	.090194	3,049	3,215
(5,940 ft.)		Section	70		.045305	.115133	2,389	2,519
	500,000		60	.069828	.052856	.122684	2,242	2,364
	1,000,000		90	.039902	.031322	.071224	3,861	4,072
1		9	70		.040272	.080174	3,430	3,617
(5,280 ft.)		Section	70		.040272	.102341	2,687	2,834
	500,000		60	.062069	.046983	.109052	2,522	2,659
	1,000,000		70	.034914	.035238	.070152	3,920	4,134
7/8		9	60		.041111	.076025	3,617	3,815
(4,620 ft.)		Section	70		.035238	.089549	3,071	3,238
	500,000		60	.054311	.041111	.095422	2,882	3,039
	1,000,000		70	.029926	.030204	.060130	4,574	4,823
3/4		9	60		.035238	.065164	4,220	4,450
(3,960 ft.)		Section	70		.030204	.076756	3,583	3,778
	500,000		60	.046552	.035238	.081790	3,362	3,546
	1,000,000		70	.024939	.025170	.050109	5,488	5,787
5/8		9	60		.029365	.054304	5,064	5,340
(3,300 ft.)		Section	70		.025170	.063963	4,299	4,534
	500,000		60	.038793	.029365	.068158	4,035	4,255
	1,000,000		70	.019951	.020136	.040087	6,860	7,234
1/2		9	60		.023492	.043443	6,330	6,675
(2,640 ft.)		Section	70		.020136	.051171	5,374	5,667
	500,000		60	.031035	.023492	.054527	5,043	5,318

1/ From a paper by Donald J. Baker, Mining Representative, I-T-E Circuit Breaker Co., Pittsburgh, Pa., and C. L. Brown, presented at the A.I.E.E. Middle Eastern District meeting, Charleston, W. Va., Sept. 29, 1953.

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TABLE 2. - Resistance and short circuit capacity, direct-current power circuits (stub-feeder applications)1/

Length of feeder, miles	Feeder size, cir. mils	Trolley-wire size	Rail weight, lb. per yard	Total copper resistance, ohm	Total track resistance, ohm	Total circuit resistance, ohm	Max. instantaneous current-amperes	
							At 275 v.	At 290 v.
	1,000,000		50	0.079803	0.112760	0.192563	1,428	1,506
2	500,000	9 Section	40	.124139	.140950	.265089	1,037	1,094
(10,560 ft.)	1,000,000		50	.092213	.112760	.204973	1,342	1,415
	500,000	4/0	40	.157005	.140950	.297955	923	973
	1,000,000		50	.074816	.105713	.180529	1,523	1,606
1-7/8	500,000	9 Section	40	.116380	.132141	.248521	1,107	1,167
(9,900 ft.)	1,000,000		50	.086449	.105713	.192162	1,431	1,509
	500,000	4/0	40	.147192	.132141	.279333	984	1,038
	1,000,000		50	.069828	.098665	.168493	1,632	1,721
1-3/4	500,000	9 Section	40	.108621	.123332	.231953	1,186	1,250
(9,240 ft.)	1,000,000		50	.080686	.098665	.179351	1,533	1,617
	500,000	4/0	40	.137379	.123332	.260711	1,055	1,112
	1,000,000		50	.064840	.091618	.156458	1,758	1,854
1-5/8	500,000	9 Section	40	.100683	.114522	.215385	1,277	1,346
(8,580 ft.)	1,000,000		50	.074923	.091618	.166541	1,651	1,741
	500,000	4/0	40	.127567	.114522	.242089	1,136	1,198
	1,000,000		50	.059853	.084570	.144423	1,904	2,008
1-1/2	500,000	9 Section	40	.093104	.105713	.198817	1,383	1,459
(7,920 ft.)	1,000,000		50	.069159	.084570	.153729	1,789	1,886
	500,000	4/0	40	.117754	.105713	.223467	1,231	1,298
	1,000,000		50	.054865	.077523	.132388	2,077	2,191
1-3/8	500,000	9 Section	40	.085345	.096903	.182248	1,509	1,591
(7,260 ft.)	1,000,000		50	.063396	.077523	.140919	1,951	2,058
	500,000	4/0	40	.107941	.096903	.204844	1,342	1,416
	1,000,000		50	.049877	.070475	.120352	2,285	2,410
1-1/4	500,000	9 Section	40	.077587	.088094	.165681	1,660	1,750
(6,600 ft.)	1,000,000		50	.057633	.070475	.128108	2,147	2,264
	500,000	4/0	40	.098128	.088094	.186222	1,477	1,557
	1,000,000		50	.044889	.063428	.108317	2,539	2,677
1-1/8	500,000	9 Section	40	.069828	.079285	.149113	1,844	1,945
(5,940 ft.)	1,000,000		50	.051870	.063428	.115298	2,385	2,515
	500,000	4/0	40	.088315	.079285	.167600	1,641	1,730
		9 Section	50	.039902	.056380	.096282	2,856	3,012
1	1,000,000	4/0	40	.046106	.070475	.116581	2,359	2,488
(5,280 ft.)		4/0	50	.078503	.056380	.134883	2,039	2,150
	500,000	9 Section	40	.062069	.070475	.132544	2,075	2,188
		9 Section	50	.034914	.049333	.084247	3,264	3,442
7/8	1,000,000	4/0	40	.040343	.061666	.102009	2,696	2,843
(4,620 ft.)		4/0	50	.068690	.049333	.118023	2,330	2,457
	500,000	9 Section	40	.054311	.061666	.115977	2,371	2,500
		9 Section	50	.029926	.042285	.072211	3,808	4,016
3/4	1,000,000	4/0	40	.034580	.052856	.087436	3,145	3,317
(3,960 ft.)		9 Section	50	.046552	.042285	.088837	3,096	3,264
	500,000	4/0	40	.058877	.052856	.111733	2,461	2,595
			50		.035238	.060177	4,570	4,819
5/8	1,000,000	9 Section	40	.024939	.044047	.068986	3,986	4,204
(3,300 ft.)			50		.035238	.084302	3,262	3,440
	500,000	4/0	40	.049064	.044047	.093111	2,953	3,115
		9 Section	50	.069828	.028190	.098018	2,806	2,959
1/2		4/0	40	.132000	.035238	.167238	1,644	1,734
(2,640 ft.)		4/0	50	.132000	.028190	.160190	1,717	1,810
		9 Section	40	.069828	.035238	.105066	2,617	2,760
		9 Section	50	.034914	.014095	.049009	5,611	5,917
1/4		4/0	40	.066000	.017619	.083619	3,289	3,468
(1,320 ft.)		4/0	50	.066000	.014095	.080095	3,433	3,621
		9 Section	40	.034914	.017619	.052533	5,235	5,520

1/ From a paper by Donald J. Baker, Mining Representative, I-T-E Circuit Breaker Co., Pittsburgh, Pa., and C. L. Brown, presented at the A.I.E.E. Middle Eastern District meeting, Charleston, W. Va., Sept. 29, 1953.

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Direct-Current Power Facilities in Four Coal Mines

The results of investigations of the power-distribution systems in four western Pennsylvania coal mines are described briefly herein to emphasize the hazardous conditions that may exist unknowingly in many coal mines. These mines are designated as A, B, C, and D for the purpose of identification in this paper.

Mine A

The direct-current power supply for main haulage and the active workings of mine A was supplied from a single substation in which a total capacity of 600 kilowatts at 275 volts was installed. A second substation on the surface at the hoisting shaft supplied direct-current power for main haulage outby and the requirements in the vicinity of the shaft. A dead block separated the two substations electrically. Short-circuit protection on the circuit in question consisted of an automatic reclosing circuit breaker in the substation, which was set to trip at 3,500 amperes overcurrent. The general layout of the direct-current power supply in the active working areas of this mine is shown in figure 2.

Locations for load tests were selected, as indicated in the figure, and tests were conducted at these locations on an idle day when all other loads could be removed. The values of resistance for the circuits involved were determined by finding the drop in voltage for a known load at each test location. The voltage at the test location was noted at the instant a load of known value was applied. The voltage thus obtained was subtracted from the voltage indicated at that instant by a recording voltmeter in the substation. The difference in voltage obtained in this manner was the voltage drop resulting from the applied load. Then, by Ohm's law the total resistance of the circuit from the substation to the point of the test was determined as follows:

$$\text{Resistance} = \frac{\text{Voltage drop}}{\text{Applied load amperes}}.$$

The instantaneous short-circuit current value was determined by substituting the resistance thus obtained in the formula: $I_s = \frac{E}{R}$, in which I_s is the short-circuit current, E the substation voltage at the instant of the short circuit, and R the total resistance of the circuit.

The results of tests made in mine A at locations, as indicated in figure 2, the theoretical resistance of the power circuits, and the instantaneous short-circuit currents are shown in table 3.

TABLE 3. - Resistance and current values, mine A

Power source, substation number	Test number	Length of circuit, feet	Total resistance, ohm[1/]		Instantaneous short-circuit current, amperes		Substation circuit breaker overcurrent setting
			Theoretical	Voltage-drop tests	Theoretical	Voltage-drop tests	
2	1	2,000	0.0122	0.0298	22,540	9,228	3,500
2	2	5,000	.0344	.0382	7,994	7,199	3,500
2	3	9,600	.1315	.1475	2,091	1,864	3,500
2	4	7,600	.1252	.1657	2,196	1,660	3,500
2	5	5,700	.0712	.1966	3,862	1,399	3,500

1/ Resistance values taken from standard tables.

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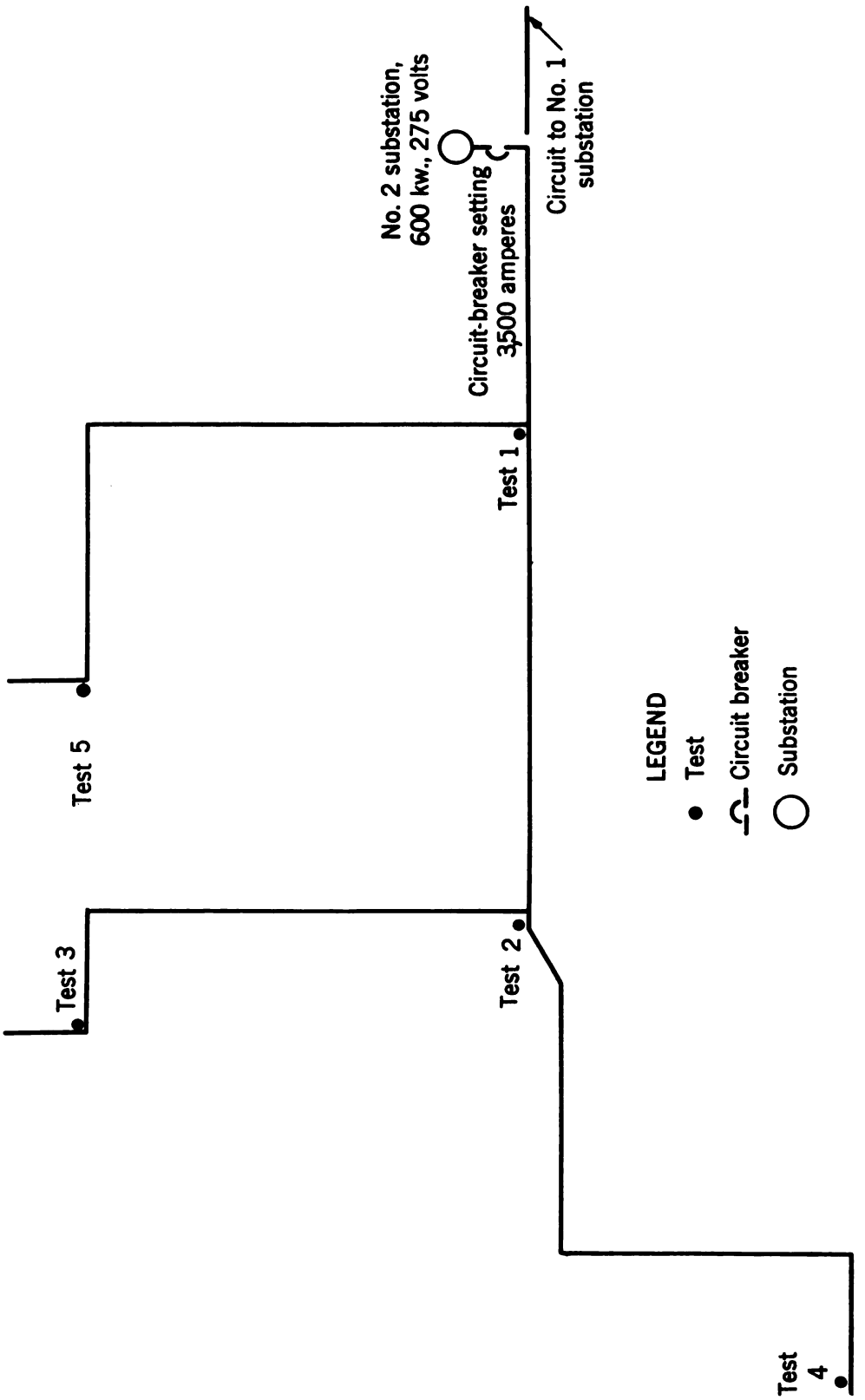

Figure 2. - Single-line diagram of direct-current power-distribution system, mine A.

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It is interesting to note from the data in table 3 that the resistance of the power circuits as obtained from voltage-drop tests in mine A was higher in each instance than the theoretical values based on the size of the conductors. This condition is found to be true in a large number of mines. The difference between the theoretical resistance and the actual resistance can be attributed to deterioration in track bonding and in some instances to high resistance of joints and switches in the insulated conductors in the circuits.

Tests 1 and 2 show adequate current-carrying capacity in the circuits between the substation and the test locations to permit short-circuit protection with the substation circuit breaker set for an overcurrent value of 3,500 amperes. The results of tests 3, 4, and 5 show definitely that short-circuit protection is not provided at these locations. Test 3 reveals that the power circuit at this location has a short-circuit capacity of about 53 percent of the overcurrent setting of the circuit breaker in the substation, and test location 4 has a short-circuit capacity of about 47 percent. It is obvious that this power-distribution system has been extended beyond the effective range of the protective device. Short circuits that occur in these unprotected areas are potential fire hazards.

The safety and efficiency of the power-distribution system in mine A could have been improved by relocating the substation nearer the load center or by installing sectionalizing circuit breakers in the three main branches. In either event, it would be necessary to improve the track bonding throughout the mine to reduce the excessive voltage drop, as indicated by the tests.

Mine B

Alternating-current was converted to 285-volt direct current by motor-generator sets, synchronous converters, and mercury-arc rectifiers. The conversion units were 300-kilowatt capacity installed in 6 substations. The overcurrent setting was 1,500 amperes for each station breaker, or a total current input of 9,000 amperes to the mine circuit. All substations were interconnected for parallel operation. The automatic-reclosing circuit breakers in the substations were the only short-circuit protective devices provided. Main haulage was by locomotives, and the trolley-wire circuit extended throughout the mine for approximately 55,000 feet. The distance between extreme substations was about 6 miles.

Voltage-drop tests were made while the mine was idle so that all connected loads could be removed and substations could be isolated as required while testing. The test procedure was the same as used in mine A. Resistance values were calculated from the voltage drop resulting from a known applied load. Figure 3 is a single line layout of the direct-current power-distribution system showing the locations of substations and test points. Table 4 shows resistance and current values for the various parts of the circuit.

An analysis of the resistance values for the various parts of the power-distribution system in mine B, as shown in table 4, reveals good maintenance of some parts of the circuit and only fair maintenance on other parts. Therefore, the deficiencies in current-carrying capacities as indicated are caused primarily from lack of proper conductor sizes for the distance of power transmission. The instantaneous short-circuit current values determined from voltage-drop tests show conclusively that a short circuit at any place on the system cannot cause the power to be removed automatically when the substations are operated in parallel. This means that when a short circuit does occur power will be fed into the fault until such time as the conductors burn clear, with the probability of starting a fire, or until the power is removed manually after discovery of the short circuit.

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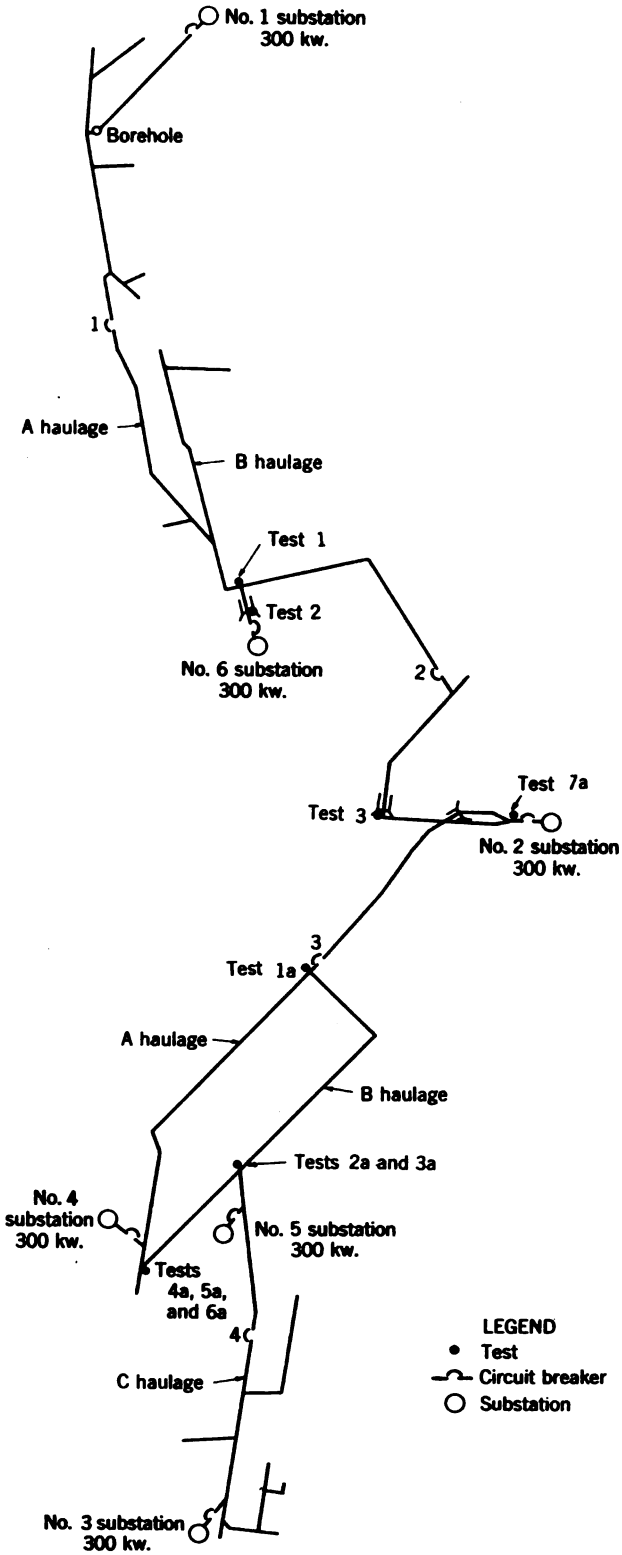

Figure 3. - Single-line diagram of direct-current power-distribution system, mine B.

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TABLE 4. - Resistance and current values, mine B

Power source, substation number	Test number	Distance from substation, feet	Total resistance, ohms 1/		Instantaneous short-circuit current, amperes		Overcurrent setting of station circuit breakers, amperes
			Theoretical	Voltage-drop tests	Theoretical	Voltage-drop tests	
1	1	9,800	0.266	0.262	1,071	1,088	1,500
1	2	10,500	.283	.285	1,007	1,000	1,500
1	3	16,500	.520	.520	548	548	1,500
2	1a	3,300	.0735	.080	3,878	3,563	1,500
2	2/ 2a	7,700 B haulage	.1475	.183	1,932	1,557	1,500
3	3a	5,200	.1560	.185	1,827	1,541	1,500
2	2/ 4a		.1586	.205	1,797	1,390	1,500
2	3/ 5a	9,200	.2039	.261	1,398	1,092	1,500
2	4/ 6a	7,650	.2074	.265	1,374	1,075	1,500
1	7a	17,800	.6016	.605	474	471	1,500

1/ Resistance values taken from standard tables.
2/ Loop circuit A and B haulage.
3/ A and B track circuit, A trolley wire and feeder only in circuit.
4/ A and B track circuit, B trolley wire and feeder only in circuit.

The distribution system in this mine has been interconnected and extended beyond the range of all substation circuit breakers. The most economical solution for improving the safety of this power-distribution system is to reduce the total length of the circuit from any one station by isolating the substations with dead blocks between them or by installing automatic circuit breakers between them to prevent feeding fault current into a short circuit from distant substations. The suggested locations of circuit breakers between substations to accomplish the desired result are indicated by 1, 2, 3, and 4 in figure 3.

Mine C

Direct-current electric power was supplied to mine C by two 280-volt, 300-kilowatt motor-generator sets installed 7,755 feet apart and connected for parallel operation. Mainhaulage was by means of locomotives, and automatic overcurrent devices, set for 1,500 amperes, were installed in each substation. Figure 4 shows a general layout of the underground power-distribution system.

Voltage-drop tests were made in a manner similar to the tests in mines A and B, and resistance values were calculated for different parts of the circuit. The results of these tests are shown in table 5. Power was supplied from No. 1 substation for all voltage-drop tests. As shown in table 5, the resistance in test 1, determined by voltage-drop tests, was nearly twice the theoretical value, consequently the instantaneous short-circuit current capacity for this part of the circuit was nearly 50 percent less than the theoretical value. Comparing the results of tests 2, 3, 4, and 5 with the results of test 1, it is found that the section of power circuit covered in test 1 is more deficient in current-carrying capacity than other sections. This fact is revealed by comparing the circuit resistance of test 1 with subsequent tests 2, 3, 4, and 5, which indicates a diminishing difference between the actual and theoretical resistance as the distance increases from the power source. Locations of tests 2 and 3 are theoretically within the range of the No. 1 substation circuit-breaker setting; however, the voltage-drop tests indicate otherwise. Any point on this circuit beyond the location of test 3 would of course be out of range of the No. 1 station circuit breaker.

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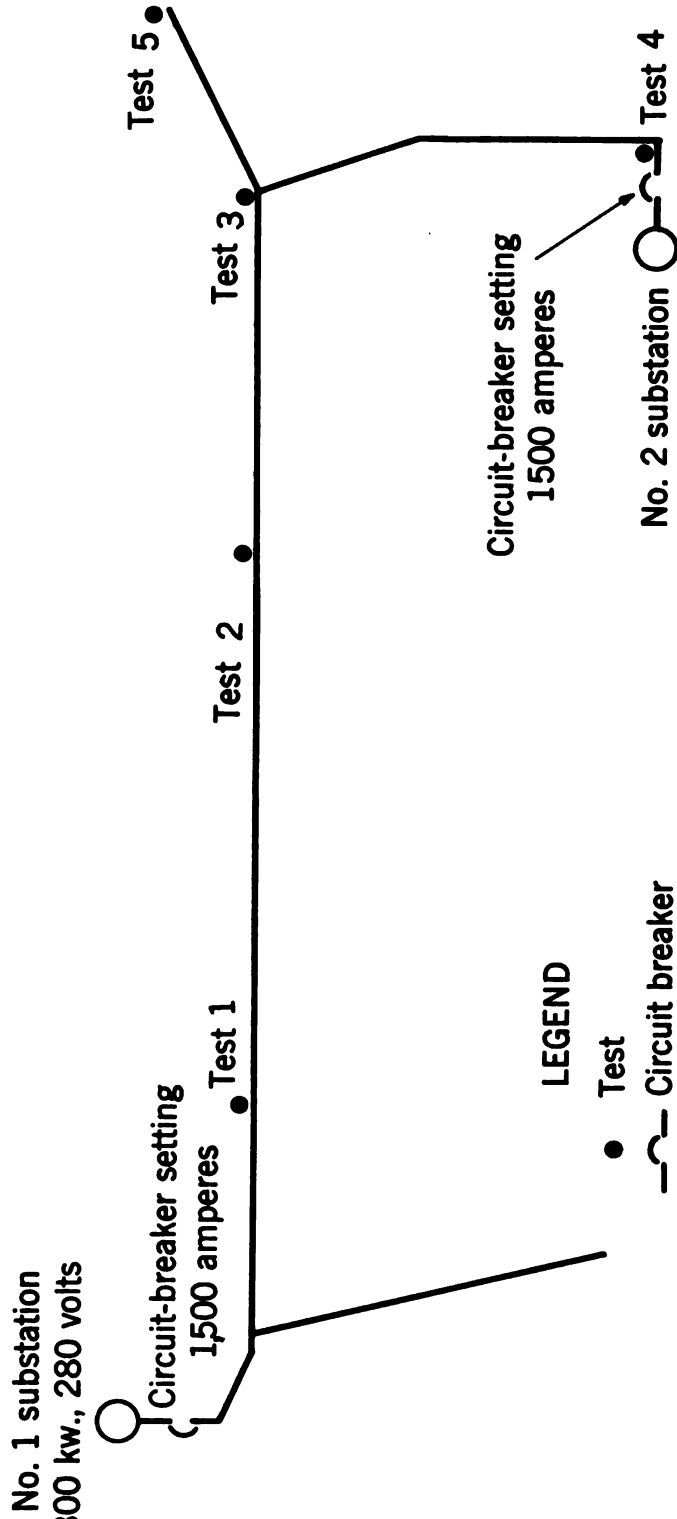

Figure 4. - Single-line diagram of direct-current power-distribution system, mine C.

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TABLE 5. - Resistance and current values, mine C

Power source, substation number	Test number	Distance from power source, feet	Total resistance, ohms[1]		Instantaneous short-circuit current, amperes		Substation breaker overcurrent setting, amperes
			Theoretical	Voltage-drop tests	Theoretical	Voltage-drop tests	
1	1	1,820	0.04254	0.0833	6,582	3,361	1,500
1	2	4,595	.10695	.1916	2,618	1,461	1,500
1	3	5,720	.13749	.1975	2,037	1,418	1,500
1	4	7,755	.24595	.3553	1,138	788	1,500
1	5	6,720	.20084	.2584	1,394	1,084	1,500

1/ Resistance values taken from standard tables.

The operating range of No. 2 substation breaker can be determined within certain limits by using the resistance values in table 5. This determination reveals that the maximum operating range of the circuit breaker is between locations of tests 1 and 2. Thus it is found that the power circuits in mine C are not protected against short circuit under many conditions of normal operation. The safety and efficiency of this power-distribution system can be improved by (1) increasing the current-carrying capacity of the circuit throughout, (2) reducing the overcurrent settings of the substation circuit breakers to extend their operating range throughout the entire circuit, or (3) installing a circuit breaker with a low overcurrent setting about midpoint between the substations.

Mine D

Direct-current power, at a nominal potential of 275 volts, was supplied to mine D by 10 substations having a total rated capacity of 4,000 kilowatts and a total output of 6,668 kilowatts based on the sum of the individual overcurrent settings. The 10 substations were connected for parallel operation to approximately 37 miles of trolley and feeder wire. Short-circuit protection for main power circuits was limited to automatic circuit breakers in the substations only, with overcurrent settings varying from 1,200 to 3,300 amperes for the individual devices. Figure 5 shows a general layout of the underground power-distribution system with the substation locations. Letters on the diagram indicate a change in conductor size. Main haulage in sections ABCDEFGO and RST is by belt conveyor. All conveyor belts are driven by direct-current motors except the belts in section GO, which are driven by alternating-current motors. Main haulage in other sections is by locomotives.

The maximum operating range of the substation circuit breakers is indicated in figure 5 by arrows and numbers corresponding to substation numbers. It should be understood that the operating ranges shown are not true for parallel operation of substations without circuit breakers installed between them but are operating ranges when power is supplied only from the substation indicated.

The investigation of the power-distribution system in mine D was limited to determinations made of the resistance of the power conductors based on their size and length for the various parts of the circuit. The results thus obtained differ from the results described for mines A, B, and C. The latter were based on voltage-drop tests made in the mines. The theoretical resistance values shown in table 6 for mine D are expected to be lower than the actual resistance if determined by measurement. The data in table 7, calculated and compiled from date in table 6, shows the effective range of the various circuit breakers in feet for a one-source supply. The importance of overcurrent settings on the effective range of a circuit

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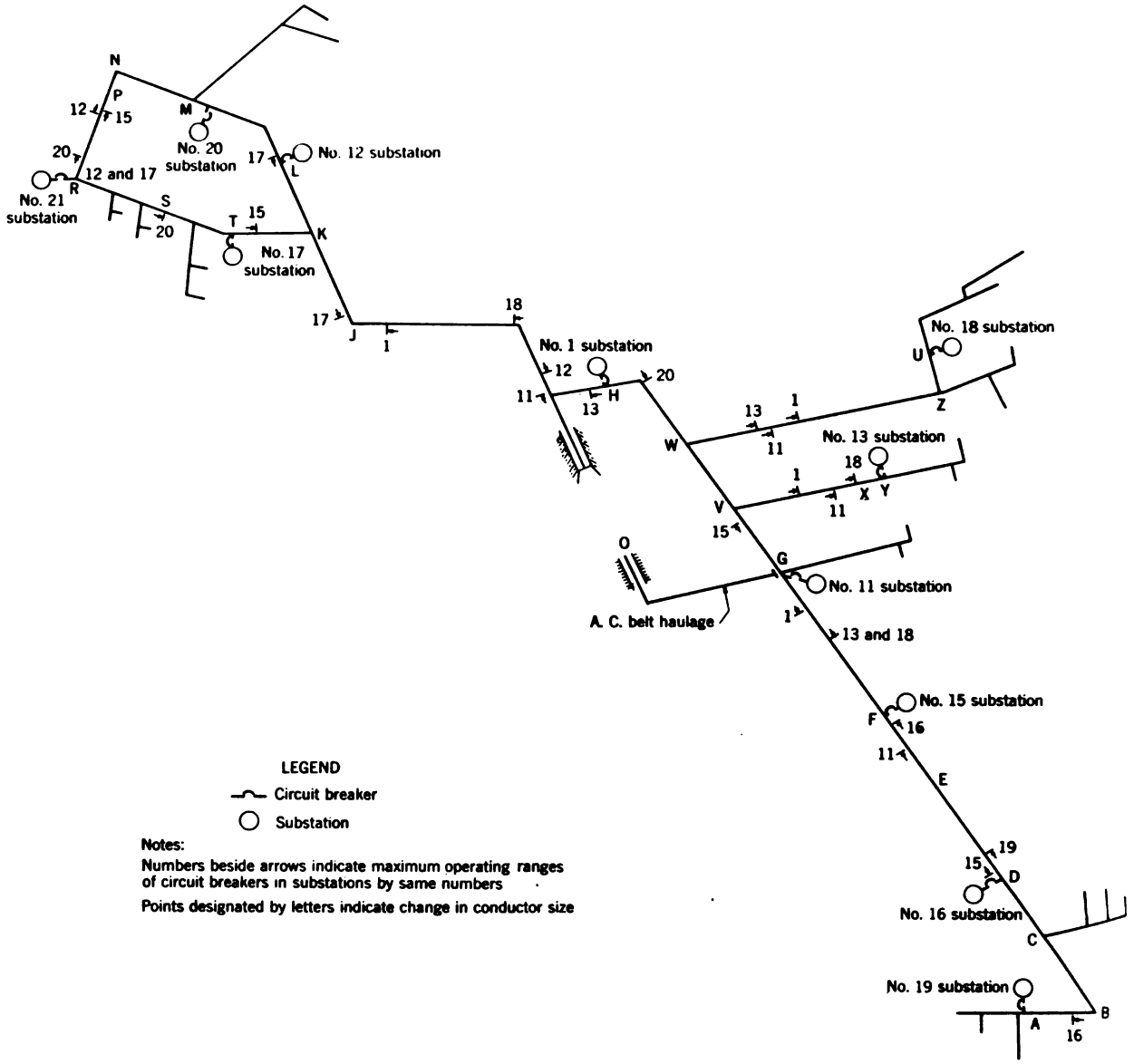

Figure 5. - Single-line diagram of direct-current power-distribution system, mine D.

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breaker is illustrated by observing the values in table 7. For example, referring to figure 5, the circuit breaker at substation 12 with an overcurrent setting of 1,800 amperes has an effective range of 10,100 feet in the direction of substation 1, whereas, the circuit breaker in substation 17 with an overcurrent setting of 3,300 amperes has an effective range of only 4,310 feet in the direction of substation 1. The resistance of the circuit is approximately the same in both cases. Casual observation of the data in table 7 shows clearly that the substation circuit breakers alone cannot be depended on to protect the underground power circuits against short circuits in mine D.

The potential fire hazard from short circuits can be reduced in this mine by isolating substations where feasible and by installing automatic circuit breakers between substations as required for protection.

TABLE 6. - Theoretical resistance of power circuits, mine D

Portion of circuit	Length of circuit, ft.	Conductor size, cm.		Resistance[1]	
		Positive	Negative	Ohm/1,000 ft.	Total, ohm
Borehole 19	525	3,000,000	3,000,000	0.00730	0.00383
A to B	1,800	500,000	500,000		
		350,000	40-lb. rail	.02087	.03757
B to C	2,400	1,000,000	70-lb. rail	.01834	.04402
C to D	1,800	1,000,000	1,000,000		
		400,000	70-lb. rail	.01221	.02198
Borehole 16	431	3,000,000	3,000,000	.00730	.00315
D to E	3,200	1,000,000	70-lb. rail	.01834	.05869
E to F	2,100	1,000,000			
		400,000	70-lb. rail	.01519	.03190
Borehole 15	411	3,000,000	3,000,000	.00730	.00300
F to G	4,400	1,000,000			
		400,000	70-lb. rail	.01519	.06684
Borehole 11	372	3,000,000	3,000,000	.00730	.00272
G to V	1,850	1,000,000	70-lb. rail		
		2-400,000	Double track	.00971	.01796
V to W	2,250	1,000,000	70-lb. rail		
		2-400,000	Double track	.00971	.02185
W to H	2,900	1,000,000	70-lb. rail		
		2-400,000	Double track	.00971	.02816
Borehole 1	135	3,000,000	3,000,000	.00730	.00099
H to J	7,300	500,000	70-lb. rail		
		2-350,000	Double track	.01267	.09249
J to K	2,400	500,000			
		350,000	70-lb. rail	.0201	.04824
K to L	1,900	500,000			
		350,000	70-lb. rail	.0201	.03819
Borehole 12	359	2,000,000	2,000,000	.01094	.00393
L to M	2,900	500,000			
		350,000	70-lb. rail	.0201	.05829

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TABLE 6. - Theoretical resistance of power circuits, mine D (Con.)

Portion of circuit	Length of circuit, ft.	Conductor size, cm.		Resistance[1]	
		Positive	Negative	Ohm/1,000 ft.	Total, ohm
Borehole 20	361	1,000,000	1,000,000	0.02188	0.00799
M to N	1,900	500,000			
		350,000	70-lb. rail	.0201	.03819
N to P	800	350,000	70-lb. rail	.0378	.03024
P to R	2,200	500,000	500,000	.04378	.09632
R to S	2,600	500,000	500,000		
		350,000	40-lb. rail	.02087	.05426
S to T	1,500	1,000,000	1,000,000		
		500,000	70-lb. rail		
		350,000		.01031	.01546
Borehole 17	361	3,000,000	3,000,000	.00730	.00264
T to K	2,000	500,000			
		350,000	70-lb. rail	.0201	.0402
V to X	3,400	500,000			
		350,000	45-lb. rail	.0243	.08262
X to Y	500	350,000	45-lb. rail	.0420	.0210
Borehole 13	292	2,000,000	2,000,000	.01094	.00319
W to Z	6,400	500,000			
		350,000	70-lb. rail	.0201	.12864
Z to U	1,000	500,000			
		350,000	45-lb. rail	.0243	.0243
Borehole 18	250	1,000,000	1,000,000	.02188	.00547

1/ Resistance values taken from standard tables.

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TABLE 7. - Maximum operating range of substation circuit breakers (one-power source only), mine D

Circuit breaker (substation No.)	Direction from substation	Maximum operating range of circuit breaker from bottom of borehole, feet	Setting of circuit breaker, amperes
19	19 to 16	6,818	2,200
16	16 to 19	4,842	3,200
16	16 to 15	4,890	
15	15 to 11	6,220	3,200
15	15 to 16	4,970	
11	11 to 15	5,580	3,200
11	11 to 1	8,525	
11	11 to 13	4,600	
11	11 to 18	6,340	
1	1 to 12	6,830	3,200
1	1 to 11	8,220	
1	1 to 13	6,650	
1	1 to 18	5,800	
13	13 to 1	9,445	1,750
13	13 to 18	7,790	
13	13 to 11	8,190	
18	18 to 1	13,930	1,200
18	18 to 11	13,800	
18	18 to 13	11,830	
12	12 to 1	10,100	1,800
12	12 to 17	8,183	
12	12 to 20	6,270	
17	17 to 12	4,099	3,300
17	17 to 1	4,310	
17	17 to 20	4,388	
20	20 to 1	15,737	1,200
20	20 to 12	11,334	
20	20 to 17	8,081	
15	15 to 17	4,852	3,200
15	15 to 20	1,940	

Short Circuit Protection of Secondary Branches

Fire hazards from secondary branch circuits, particularly trailing cables, are of much concern in coal mines. Numerous fires have occurred in trailing cables that connect mobile equipment to the power source. Common causes of fires from this source are:

1. Defective splices (improperly made splice or temporary splice left in service too long.
2. Power conductors in trailing cables too small.
3. Inadequate short-circuit protection.
4. Inadequate voltage at power tap.
5. Damaged cable owing to:
   (a) Overloading as a result of improper handling or maintenance of equipment.
   (b) Being run over or pinched by equipment.
   (c) Improper reeling and spooling.

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Much can be done to alleviate the fire hazard from trailing cables. Care in selecting, applying, and maintaining cables is recognized as being important. The selection and application of proper devices for protection against short circuits and good voltage regulation are essential in preventing fires from defective trailing cables. Most cable manufacturers are now considering improvements in construction features as an aid to better cable performance.

Branch circuits feeding isolated loads may be potentially hazardous if not protected against roof falls and short circuits. Fires originating in isolated areas frequently get out of control before being discovered. Good operating practice dictates that protection against these hazards be provided and that power be removed from isolated circuits when not needed.

SUMMARY

Fire hazards from underground power-distribution systems are at a minimum only where the system is designed in accordance with accepted good engineering practices and protected in a manner so that a direct short circuit at any place on the system will cause power to be removed automatically from the affected part of the system. Unfortunately, a large number of mines do not meet these requirements. The cost of minimizing fire hazards where they exist on underground power systems will vary for the different mines, depending upon the magnitude of the deficiency. The manner in which the correction is made is not always limited to the application of automatic protective devices. The most practical solution in any event requires proper engineering knowledge of the problem. Common methods of providing adequate short-circuit protection where such deficiencies exist are:

1. Increase current-carrying capacity of power circuits by adding copper or improving track bonding as required.

2. Maintain substations as close to load centers as is practicable.

3. Isolate substations where feasible.

4. Reduce settings of automatic overcurrent devices to conform to safe current-carrying capacity of the circuit.

5. Check locations of protective devices for maximum effectiveness. Mine development often requires relocation of devices.

6. Where immediate improvements cannot be made, reduce length of power circuits by discontinuing work in remote areas.

7. Install automatic overcurrent devices as required.

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